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Technical Review of Robotic Complexes for Underground Mining

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Abstract. The paper contains classifies robots for work in mines, the tasks they perform, compares developments in this area with a description of the difficulties and solutions which have found. Social and economic difficulties that often hamper the process of automation and robotization of underground mining are given.

1. Introduction

In the modern world, human life has the highest value, and therefore workers are replaced by robots at hazardous production facilities, this process is called production robotization. When robotization occurs, the group technological chains create, which is part of the automation of production cycles. These systems can perform actions in dangerous conditions that were previously carried out by people and sometimes resulted in victims, the occurrence of severe aftereffects to health.

Robotic systems using, in which automatically operating mechanisms and devices implement the entire technological process, allows achieving higher efficiency and safety of work [14,15,18].

Underground mining robots is a promising technology of our century, which is seen as part of "the unmanned mine"[1, 15]. Using robotic systems for open mining is already well developed, there are a significant number of mass-produced devices, for example, a loading-unloading machine Sandvik LH621 [2]. For underground mining, robots are still used only on sites with well-developed infrastructure (salt mines), most often they are autonomous vehicles used in previously prepared areas of operation. Preparation includes the separation of the autonomous vehicle operation zone from areas where people are present, the placement of indicative signs, etc. [3]. Developing mining robots, it is necessary that they can work in conditions of poor visibility, with many obstacles, with a high content of gases (carbon dioxide, methane, carbon oxide), high temperature, humidity, and dust.

Using robots for underground mining allows:

- improve employee safety;
- perform exploration (e.g. mapping) and monitoring work in potentially dangerous areas, access to which is restricted to human safety regulations;
- carry out rescue operations in the emergency event.

2. Development directions of robotic complexes for underground mining

The creation and development of such prototypes are carried out both in Russia and in foreign countries [4]. Engineers equip robots with explosive gas sensors to alert the dispatcher about exceeding threshold concentrations, ultrasonic systems for spatial orientation, video cameras, automatic manipulators or boom, and other devices to perform assigned tasks. Table 1 shows examples of developed robotic devices with a description of the functions performed and design features.

Table 1. Development of robots in accordance with the functions performed for underground mining [4,19].

Developer / product	Functions	Design features
	Operation	
Perm National Research Polytechnic University, Russia / Robot miner	Detection of gas impurities in the air. If the threshold gas concentrations are exceeded, an alarm is sent to the control room	Spider design (walking 8-legged robot), with subsystems: methane sensor, ultrasonic distance measurement sensor, control system
Montabert, France / Robotic Drilling Rig "Robofore"	Drilling for a specific program	Robotic platform with two automatic manipulators
NitroNobelMec, Sweden / mobile manipulators HF-51 и EG-33	Loading wells with explosives in loose workings	Mounted on a transport base charging complex consisting of a bunker for solid and liquid components with loading and unloading windows, auger feeding system and mixing components of explosive, auger mixer-supercharger
BrokkAB, Sweden / Disassembly robot	Dismantling works: drilling wells without the use of heavy machinery, ruffling pins, dismantling blockages, crushing of oversize	Transport base equipped with a maneuverable manipulator (turning range from 270° to 360°)
TopTec Spezialmachinen GmbH, Германия / Демонтажный робот	Dismantling works during mining operations	Frame protective frame, separate oil cooling circuit, enhanced safety margin, retractable boom
	Salvation	
Institute of Technology, Genoa, Italy / Robot Walk-Man	Rescue work, eliminates gas leakage, extinguishes fires, opens damaged doors	Humanoid design, equipped with 32 engines, cameras, 3D laser scanner, microphone.
Kaicheng Corporation, Hebei Province, China [14] / Rescue Robot	It reaches the scene of the accident and transmits the received information to the rescuers. Equipped with the function of self-positioning, collecting and broadcasting information	The frame structure is equipped with four wheels, with mounted equipment on the central platform.
	Exploration	
Special Design and Technology Bureau of Applied Robotics, Russia Mobile robotic complex MRK -27	Visual intelligence; gas, chemical and radiation survey areas; work under conditions of chemical contamination and areas of high radioactivity; transportation of items	Single-section chassis with variable track geometry; 5-power manipulator + gripper; electromechanical transmission; control system; power supply system, operator post (trolley and/or case); radio channel; technological control panel. Equipped with additional devices

Conditionally, robots for underground mining can be classified according to the main function performed:

- Exploration: carrying out mapping of mines, investigate the possibility of safe operation, carrying out instrumental and instrumental reconnaissance, assess the situation after an accident, etc.
- Salvation: to carry out the salvation of people, for example, clearing the way or debris; carrying out the loading of a person for his evacuation; delivering necessary for victims, restore sensor networks, etc.
- Operation: performing various tasks in the mine, monitoring the state of the environment (concentration of combustible gases, temperature), moving objects, drilling, dismantling, etc.

Depending on the task, different robotized complexes can combine several functions in one equipment.

One of the first tasks is mine exploration and mapping. To solve the problem of mapping and navigation in the mine, various solutions were used. For example, in 1999, Scheding et al. [1] developed an underground dump truck equipped with sensor and sonar sensors, a laser scanner and a package of inertial measurement units. The tests were carried out on a pre-prepared territory: an underground drift of an abandoned Mount Isa mine in Queensland, 150 m long with retroreflective strips. As a result of the tests conducted on the accuracy of navigation, it was 10 cm and it was revealed that wheel slippage affects this indicator.

In 2003, Ferguson et al. [1] conducted tests on the Groundhog, a robot with a laser scanner, immersion sensors, onboard computing, and video recording equipment. Using two laser scanners, a 2D model of the environment and local 3D maps were created. The robot investigated 40 m and 308 m sections of abandoned coal mines. Groundhog was rather cumbersome, its total weight was 545 kg, which allowed him to explore only wide sections of the mine.

Zlot and Bosse in 2014 [1] using a pickup truck equipped with several laser scanners created 3D models of a modern copper-gold mine in New South Wales. A total of 113 minutes was spent on exploring the 17 km of mine workings. In addition to scanners, the pickup was equipped with inertial measuring units to calculate the path of the sensor platform during movement. As a result of the post-processing, a 3D model of the mine was obtained with minor flaws, but geometrically close to real data.

3. The level of robotic systems development

Technical University Bergakademie Freiberg, Germany, used the results of these studies to create new robots Alexander (project Mining-Rox) and Julius (project ARIDuA). Both samples are designed to scan mines and create 2D and 3D maps [9]. The Mining-Rox project is aimed at creating a mobile robot for underground mining, and the ARIDuA project is studying the synergy between the Internet of Things (IoT) and robotics.

3.1. Alexander robot

The Mining-RoX project is developing mobile robots for autonomous reconnaissance of underground mines. Project studies are conducted at the Reiche Zeche mine in Freiberg. The robot complies with the following parameters: anti-shock protection, water and humidity protection, temperature operation range 5-15°C, the road clearance must be at least 13 cm, the dimensions should not exceed 80 × 180 × 150 cm and weight not more than 300 kg, additional lighting.

For the robot, the Husky A200 mobile platform from Clearpath Robotics (Figure 1) was selected, having a maximum movement speed of 1 m/s and a load capacity of 75 kg. The platform has a programming interface for controlling the drive. Detailed information about the basic equipment is given in Table 2.

To perform the tasks, the robot is equipped with sensors of visual perception and sensors of various environmental parameters (temperature, humidity), the accuracy of which is maintained at 0-5 m in the temperature range from 5 to 15°C. Table 2 presents information on all sensors used in this sample.

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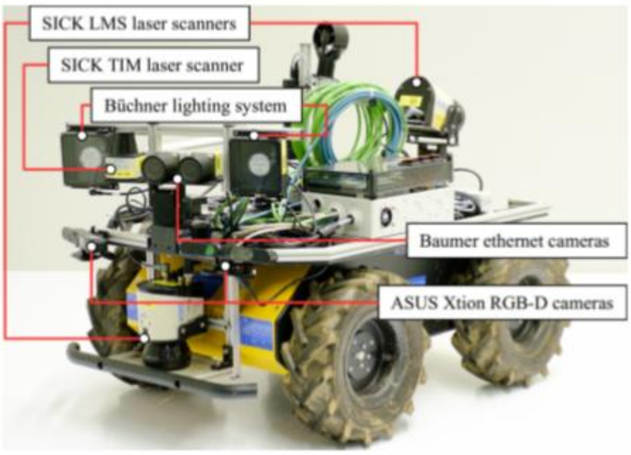
Shooting using a laser scanner gives a cloud of points, which allows rebuilding a 3D map, in addition, the laser allows to detect obstacles in the path of the robot. The front panel of the robot with an angle of 45 ° has two cameras of RGB-D depth. This type of camera is selected due to low consumption, and they use structured light [1]. They project an infrared pattern onto the surface, which is then captured by an optical sensor.). Additionally, installed laser scanner (SICK TIM 551). A scanner (SICK LMS 111) is installed on the rear panel of the robot, creating a vertical section of the study area. All hardware is mounted on a tray-tilt unit (PTU). The distance between the cameras is selected in such a way that the entire scanning area is captured and in the post-processing, it is possible to obtain a stereo reconstruction - a three-dimensional reconstruction of objects from two-dimensional images.



Cameras, a laser scanner and a lighting system at the front are mounted on a tray-tilt unit (PTU). Environmental sensors are not visible in the photo.

To obtain independent measurements of the air speed, Alexandr contains two anemometers, one of which is attached to the highest point of the robot (upper plate). Similarly installed temperature measurement sensor.

Figure 1. Alexander robot.

Wheel odometry and inertial measuring unit data allow controlling the movement of the robot, track roll and pitch. The robot is equipped with two light sources: one with a low radiation angle (for lighting remote areas), the other - a high one (for closer areas). Both light sources are controlled by software that controls lighting while driving. A recorder for measuring the relative humidity of air is installed in the upper plate in the center of the robot. Most sensors are connected to the robot via USB, which allows controlling their measurement.

All sensors and actuators, as well as the robot platform itself, are connected to the robot control PC with Linux OS, which is expanded by ROS using the Indigo version. It allows you to monitor the status of the robot and the collected sensor data in a virtual 3D environment. Scan data is published to ROS over an Ethernet connection using the ROS driver provided by SICK. In addition, ROS provides the ability to write any sensor data to a hard disk, so that it can be replayed afterwards [5].

The tests of the Alexander were carried out at a depth of 147 m in two sections of 50 m each. The first section consisted of a straight mine working with rails, and the second - the ore drift. The robot generated a navigation map, measured temperature, air humidity, and airspeed and tied these measurements to the generated map. It took 10 minutes to determine the environmental parameters. The results obtained were used by the operator in real-time. All obtained measurements remained in the PC memory.

During the tests, several shortcomings were revealed: the anemometer measured a constant air velocity of 0.1 m / s, which is lower than the minimum sensor value, the thermometer readings were 2° C higher than the anemometer readings, the light source with a high extraction angle was used by 80%, and from low - only by 20%.

3.2. Robot Julius

As part of this project, the interaction between the robot and the IoT infrastructure consisting of Smart Sensor Boxes (SSB, intelligent sensor) deployed throughout the mine was investigated. Each SSB

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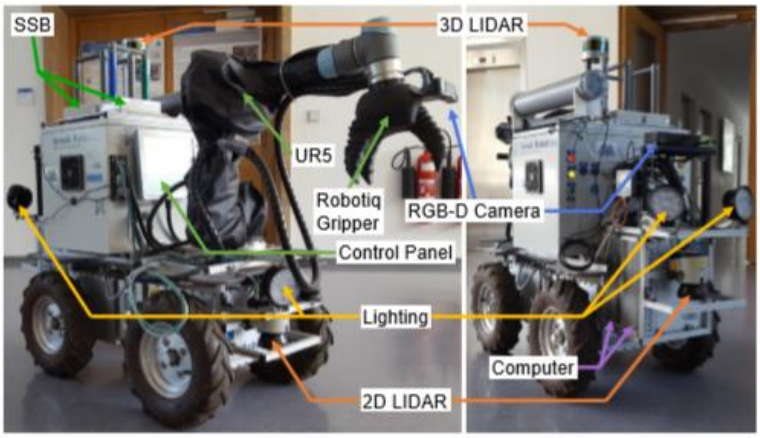
contains different sensors for environmental monitoring, which together form a wireless sensor network (WSN). SSB transmit data to the access point for external use [6]. Julius's robot locates the sensor, reducing its own localization error, self-installing, rearranging, or removing SSB underground. For these purposes, a manipulator (arm) is provided, using which the robot surveys the unexplored terrain. Created maps can be used to create 3D models. The robot contains standard sensors, a manipulation unit, computational units and a power source, which makes it easy to reproduce. For Julius, Innok Robotics platform was developed [7], it is represented by four 16-inch wheels equipped with odometer sensor, each wheel is driven by a special electric motor with a drive, which ensures maximum maneuverability (Figure 3). The parameters of the main equipment are shown in table 4.



On board are several optical sensors: VLP-16 (top) Kinect ONE (right) SICK LMS (bottom left and right). There are two powerful computers (bottom right) and a lighting system. Julius battery power is enough for 6 hours of work on the surface and 4 hours of work underground

Figure 2. The research robot Julius is equipped with a robotic arm (UR5).

Optical sensors and their characteristics are shown in Table 3. Kinect is used as an RGB-D camera. To implement the manipulator on its side surface, a second, smaller RGB-D camera (Asus Xtion) is installed. On the back of the robot is installed camera depth. To broaden the view, a 3D laser scanner is installed on the top panel, providing 360 ° continuous viewing. To eliminate blind spots, the robot is equipped with a 2D laser scanner that allows you to detect obstacles.

The universal robotic arm UR5 has 6 joints, each of which has a working area of 360 °, which provides a working space of 85 cm. A body's own weight is 18.4 kg (total weight of Julius is 138 kg). Hand control takes place via Ethernet and a robot operating system driver (ROS). Hand loading capacity 5 kg. To protect against water, it is additionally protected by a rubber bushing.

4. Conclusions

The introduction of robotic technologies allows the development of deep-seated coal seams at a depth of over 1-5 km [17]. Production can be carried out in a continuous, round-the-clock mode since the robot miner can be constantly underground. On the one hand, this solves the problem of safety in mines, but on the other hand, this factor affects the number of jobs, which already causes excitement and resistance to the process of automation and robotization among workers, for example, in the BA Kansakea study [16] it was found that One third of workers (33%) in Ghana will have to change their profession or stop working, as businesses are city-forming and there is no other work as the process automation increases. Also, this process is hampered by the authorities of the region to avoid unemployment. To reduce the resistance, in the first place, the processes that are still poorly executed by humans should be automated/robotized in the first place. For example, mapping at a depth of 1-5 km or in previously submerged mines is not performed in enough volume due to the potentially high danger to humans. Developments in this area are carried out in most countries of the world. Analysis of existing developments showed that the main problems are the accuracy of the data obtained (inconsistency of the plan obtained by the sample with the original one), data transmission in continuous mode, sample dimensions, throughput, power, but the achieved accuracy parameters, sample operation time, the ability to store data in the internal mode. PCs make it possible to predict the growth of development in this area, and, accordingly, increase the safety and efficiency of the development of deep mines.

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